# Zonation of Central U. S. Earthquake Sources

G. L. Hempen
*USAED-St. Louis, St. Louis, Missouri*

M. J. Klosterman
*USAED-St. Louis, St. Louis, Missouri*

B. H. Moore
*USAED-St. Louis, St. Louis, Missouri*

John D. Rockaway
*Missouri University of Science and Technology*

Gerald B. Rupert
*Missouri University of Science and Technology*

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**G. L. Hempen, M. J. Klosterman, B. H. Moore**
**Geophysicist, Geologist, Civil Engineer: USAED-St. Louis, St. Louis, Missouri**

**J. D. Rockaway, G. B. Rupert**
**Professors, Geol. Eng., Geophysics: University of Missouri-Rolla, Rolla, Missouri**

SYNOPSIS A variety of analyses are utilized in developing potential earthquake ground shaking at a specific location. Geological procedures for estimating causes of earthquakes are fundamental to the prediction of ground motions. Evaluations of geologic factors compliment mathematical assessments of seismological data. Earthquake potential in the Central United States is predicted using the concept of seismic source zones due to the difficulty of determining active faults. Resolution of these geographic source zones is dependent upon knowledge of historic seismicity, pertinent geologic features, and causative tectonics. Regardless of the method used to delineate source zones, these zones must be geologically and seismologically unique. Statistical testing of historic earthquake catalogues is required for reduction of the data base. The resolution of zones is an iterative process of bounding the zones and determining recurrence rates. Earthquake potential and risk assessment should be understood by the owner and the designer of a facility.

## INTRODUCTION

Risks due to earthquakes may need to be considered in order to plan and develop a structure. An earthquake engineer may be requested by the designer to determine shaking due to potential earthquakes. The earthquake engineer utilizes a variety of analyses to evaluate risk. Qualitative, geologic evaluations should be developed along with numerical reductions of historic seismicity to determine the design earthquake(s).

This paper indicates the theory of and analysis for earthquake predictions in the Central United States. The areas to be developed are the concept of earthquake source zones; the procedures to evaluate the historic seismicity, to relate geology with earthquake production, and to determine source zones; and the earthquake risk responsibilities of the owner, designer, and earthquake engineer.

## MODELING OF EARTHQUAKE OCCURRENCE

Although the Central United States is latticed with Paleozoic faults, no active earthquake faults are recognized. The "New Madrid" fault is indicated by lineations of microearthquakes and larger events. The New Madrid fault is becoming better defined by the location of recent earthquakes and by geophysical studies in the region, but the mechanism inducing the stresses is not well understood.

Knowledge of active faults at plate margins yields a specific methodology of evaluating earthquake probability. One approach to postulating earthquake potential, calculated by locating events on active faults, is common in the Western United States. A different procedure is anticipated if the slip mechanism (fault) of recurring earthquakes cannot be distinguished. The earthquake source zone concept of bounding geographic areas may be adopted where active faults are unknown.

The earthquake source zone concept relies on basic parameters: unbiased seismic history, tectonics, illustrative geologic features, and unique source zones. Regional tectonics acting on, or indicated by, geologic features is responsible for the stress increases which are released as earthquakes. Recognition of the geologic features and their relation to the causative intra-plate tectonics is necessary to the constraint of the zones. Regional, geologic domains should bound source zones, such that no seismotectonic zone would contain portions of more than one, pertinent, regional feature. The source areas of earthquakes are assumed sufficiently unique from adjacent zones that the limits of these areas may be defined. This individuality of domains implies that the earthquake generation rate, defined by a recurrence relation, differs among zones. Note the subtlety of these deductions: if two source zones have different geologic geneses but produce similar rates of earthquakes, the two will be indistinguishable. Only one zone would be resolved. Further, there is no flaw due to these implications. The calculated risk of earthquakes is slightly more conservative (greater) if one zone is chosen, rather than two zones of similar recurrence rates. Recorded seismicity and the descriptive geologic structure must be adequately understood to resolve the earthquake source areas.

Potential earthquakes for each seismotectonic zone are considered capable of occurring anywhere within the confines of the zone. The distribution of earthquake magnitudes is resolved from the seismic history and geology of the zones.

## HISTORIC SEISMICITY

The information on earthquakes prior to the aovent of instrumentally located events is based on written accounts of damage caused by the earthquakes or physical evidence. Newspaper records have been very useful to the evaluation of seismicity for the Central United States, Docekal (1970). Physical evidence, Fuller (1912), and geochronology have had a more limited use in enumerating events and establishing relative sizes of events.

A data base of historic seismicity, itemized from various references or evaluated independently, is the first important task in assessing potential events. Prior to the establishment of the St. Louis University seismic array for the New Madrid, Missouri area in 1973, considerable inaccuracies were inherent in the reduction of hypocenters and magnitudes for smaller earthquakes of the Central United States. Seismicity catalogues are biased and incomplete in spatial, time series, and frequency distributions.

The bias in the distributions of earthquakes may be reduced by evaluation of time and magnitude increments of the seismicity data base. Contouring geographically the number of epicenters (density), which are contained within unit areas for a given magnitude interval since a given date, is a useful method of diminishing spatial and frequency error. This distribution of earthquakes is very useful in spatially comparing a seismic data base to regional geologic features.

## GEOLOGY

Geologic structure should be considered for the bounding of earthquake source zones, in conjunction with the spatial distribution of the historic seismicity catalogue. Major geologic regimes, which have been active over long periods of time, are likely to be related to intra-plate tectonics. The areal extent of major geologic structure must be considered in bounding unique seismotectonic zones. The eastern portion of the Interior Platform has several systems on its flanks which shall not be considered: the Ouchita and Appalachian Systems and the Canadian Shield. The Mississippi Embayment will be considered, although the Coastal Plains, as whole, will not.

The intra-plate tectonics affecting geologic structure and producing the stresses released as earthquakes is not well understood for the Central United States. The relation of the driving tectonic mechanisms to the Mississippi Embayment is of considerable interest to the scientific community. Hypotheses on the tectonic forces and their action on intra-plate crust will undoubtedly assist in the resolution of earthquake recurrence. Considering the lack of knowledge of the tectonic framework, basement geologic features can be utilized as evidence of an active stress-producing regime. Structural adjustments of the basement are a long time frame effect of tectonics. In the short time frame, earthquakes are the rapid release of strain increased beyond the capacity of the local rock strength. Basement geology, therefore, should be a diagnostic of earthquake production.

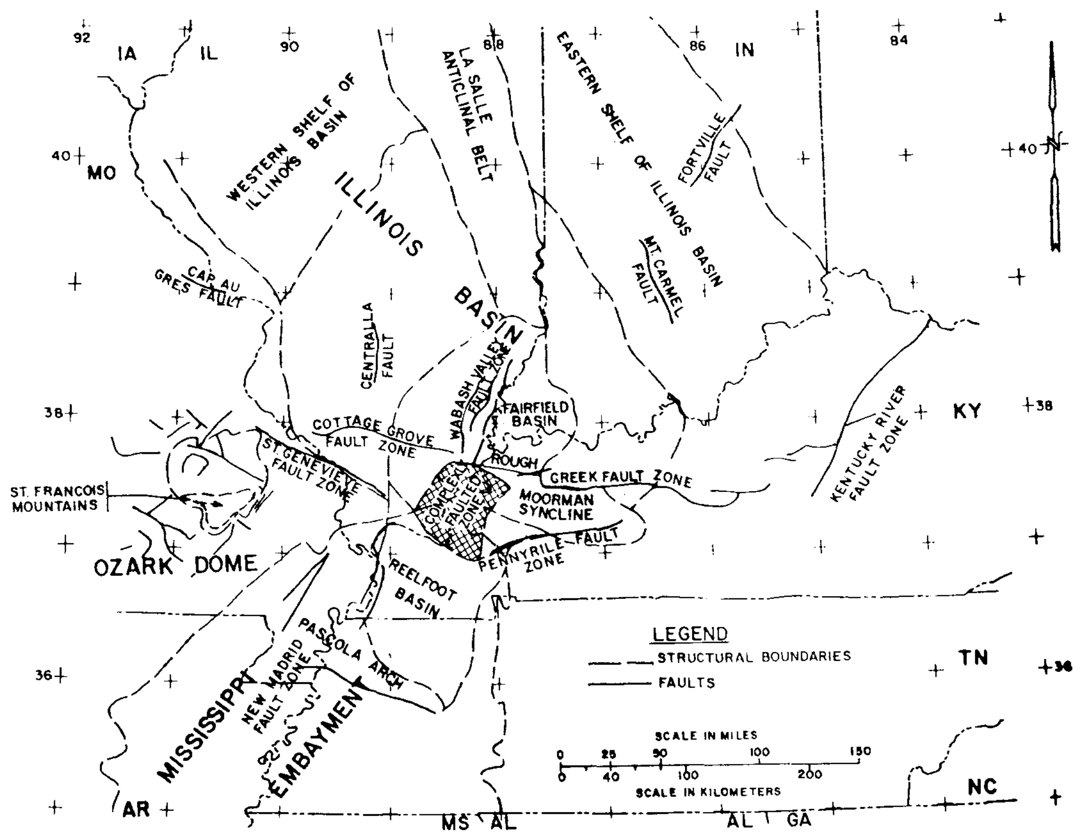


Figure 1. Basement Geologic Structure in the Central United States, USAED-St. Louis (1980).

Precambrian structure (the current structure of basement rock) and its history is particularly important to the resolution of earthquake source zones. Earthquake generation is probably related to major features affecting the Precambrian: Reelfoot Basin (Rift?), Mississippi Embayment, Ozark Uplift, Illinois (Fairfield) Basin. Figure 1 depicts basement geologic structure as determined by USAED-St. Louis (1980).

The existing structure of basement rock is largely due to differential motion during Paleozoic times. The Reelfoot Basin and the Mid-Continent Gravity High (Kansas northeast to Michigan) were active during Precambrian time - probably as rifts. Development of the Cincinnati Arch, Ozark Dome, and Illinois Basin has occurred over much of the Paleozoic. Major faulting along the Ste. Genevieve, Cottage Grove, and Rough Creek Fault Zones occurred prior to and during the Paleozoic. Strike slip and vertical motion along these fault zones is complex, but certainly occurred in weaker or on recurring slip locations to relieve the strain of differentially active geologic structures.

Other geologic considerations are pertinent to the evaluation of seismotectonic zones. Gravity and aeromagnetic mapping, analyses of stress measurements, and evaluations of data from seismic arrays of instrumentally-recorded earthquakes complete the geologic evaluation. Gravity and aeromagnetic maps from data reduced on a regional scale identify trends in the surface of the basement rock. Linear, northeast oriented features extending from the Mississippi Embayment into the Illinois Basin, possibly indicating rift boundaries, are shown by these maps. Intrusive bodies, indicative of deep crustal rupture, can also be recognized in the basement surface with these regional, geophysical maps. Stress measurements, although not abundant, indicate the maximum, horizontal, compressive stress trends northeast-southwest for the Interior Platform. The relation of the principle stress direction with weak crustal zones allows interpretations of a structure's ability to accummulate stress which could be released as earthquakes. Arrays of seismic recording stations produce data which locate earthquakes in time and space. Seismic array data may also be utilized for fault plane solutions, crustal velocity models, and attenuation assessments. A fault plane solution indicates two radiation patterns by which an earthquake could have released its initial displacement. The stress patterns depicted by several fault plane solutions indicate the likelihood that repeated events are due to the same cause. Velocity models in the vicinity of seismic stations are used for more accurate reduction of data from the recording stations. Naturally, these velocity models may be used in geologic interpretations of the crust.

## REDUCTION OF ZONAL DATA

The resolution of seismotectonic zones is an iterative procedure of bounding the zones and determining recurrence rates of earthquakes. Bounding the zones geographically relates the geologic features to the distribution of historic earthquakes. Recurrence rates may only be computed after reducing the bias in the data. Comparisons between the geologic domains, recurrence rates, and stress producing mechanisms determine uniqueness of the source zones.

Boundaries of the seismotectonic zones are defined using the limits of major geologic features; then smaller structural features and/or the density of epicenters specify other limits of zones. Initially, there may be a large number of zones or various boundaries for a single zone to be evaluated, because the geologic and historic seismicity data are subjective.

The catalogue of historic seismicity for each preliminary zone is statistically assessed. The seismicity data base is prejudiced by the small events of an earthquake series (only the main event is pertinent), by an inaccurate or incomplete reporting of shocks, by a paucity of events within a size interval, and by large scatter in the data. Reductions in the bias of the historic seismicity is important prior to comparing zones among each other.

Only the largest event is important for several shocks occurring near the same geographic coordinates within a few tens of days. Small events associated with a main earthquake are eliminated in order that recurrence rates reflect the largest releases of energy. For some zones, the recurrence rate would be heavily biased to small events if fore- and aftershocks were not deleted.

The zonal seismicity is appraised for the periods in time the data is complete by increments of earthquake size. The record is incomplete to this day for events less than body-wave magnitude 3. This completeness evaluation is conservative because it usually defines the duration with largest number of events per year. Periods of completeness will be longer for larger earthquakes since larger events, felt over greater areas or producing more damage, are more likely to be reported. Some error due to this procedure may occur since earthquakes are often episodic in nature. This error will be reduced by comparing completeness periods between zones. Stepp (1973), Nuttli and Herrmann (1978), and USAED-St.Louis (1980) have used various statistical procedures to assess completeness.

Recurrence rate estimates are computed from the seismic record of each zone corrected for completeness. The inverse of the average period between events for a magnitude increment is the occurrence probability, the number of events per year. Exceedance probability, N, is the likelihood that an earthquake annually will be exceeded. The exceedance proabability is the sum of the occurrence probabilities for all events greater than and equal to the size of earthquake being assessed. For earthquake size by magnitude, m, the recurrence relation takes the linear form,

$$\log N = a + b\,m. \qquad (1)$$

The intercept, a, is a measure of the expected number of events annually for that zone. The slope of equation (1), b, is the relative proportion of small earthquakes to larger ones in equal time frames.

Comparisons among the zones are made to assure that the input information and the statistical solutions are appropriate. The contrast of geologic domains, tectonic influence, and assessment of recurrence rates define the uniqueness of the zone choices. Other sets of zone data may be analyzed by adjusting zone boundaries or adding (and deleting) zones. The desired final outcome is a set of unique zones, which differ in geologic factors and return rates of earthquakes.

## EARTHQUAKE RISK

The design earthquake and the later analyses to assess risk are developed on the basis of the seismotectonic zones. The owner has the responsibility to assign the allowable hazard to life (if any) or property. The designer and earthquake engineer should share responsibility in the measure of the allowable hazard and the procedure to assess that hazard.

The owner may wish to consider the allowable risk of an earthquake in a variety of terms: fatalities due to loss of the structure, the economic terms of facility or business loss, or more direct terms of maximum motion or return periods of earthquakes. The designer must relate the owner's intent of allowable risk to a quantity, with which he can analyze the structure and which the earthquake engineer is capable of predicting. The important point is that the owner, designer, and earthquake engineer must understand the risk each utilizes and the limits to which that earthquake potential may be evaluated.

The earthquake engineer with input from the designer resolves the design earthquake, the accuracy to which it should be predicted, and the type of procedure to gauge the design earthquake. The term design earthquake differs in meaning from design risk parameter. The design earthquake may be an individual or a set of magnitudes, site or epicentral intensities, or return periods. The design risk parameter (also called the design ground motion) is that value the designer will utilize in analysis of the structure. The design risk quantity could be in terms of maximum components of motion, motion at specific frequencies, or response spectra. The earthquake engineer must assess the level and type of procedures to assess first, the design earthquake, and second, the design risk parameter.

## CONCLUSIONS

The earthquake source zone concept should be used to assess earthquake potential in the Central United States, since active faults are not recognized. Unique source zones are defined by geologic features (which reflect intra-plate tectonics) and by seismic history. Once zones are derived, all potential earthquakes are considered capable of occurring anywhere within the boundaries of the zones.

The data base of historic seismicity, although biased, is essential to the evaluation of potential earthquakes. A convenient method to evaluate the seismic history is to geographically contour the density of epicenters within unit areas for earthquakes after a given date of a specific magnitude interval.

The area discussed is the Eastern portion of the Interior Platform. Basement geologic structure is considered to reflect the intra-plate tectonics. The intra-plate tectonics is not known directly. Geologic features, as refined by geophysical and seismological data, and spatial distribution of the historic seismicity characterize the boundaries of the seismotectonic zones.

The bias of the catalogue of events within each zone must be reduced. Very small earthquakes and fore- and aftershocks are deleted from the list, leaving only the main earthquake of any series. Periods of completeness for each zone are determined to find the proper occurrence probabilities for the increments of magnitude. Recurrence curves are computed from the occurrence probability data. Lastly, the seismotectonic zones are evaluated for uniqueness in geologic domain, tectonic influence, and earthquake recurrence relations.

The allowable hazard due to an earthquake must be assigned by the owner of the facility. The design risk parameter is assessed in terms applicable to designer and producible by the earthquake engineer. The owner, designer, and earthquake engineer should fully comprehend the hazard parameter that each has specified.

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